Effect of CTE on Fatigue Cracking of Stainless Steel Vessels

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Abstract

Visual examination of lithium hydride reactor vessels revealed cracks that were adjacent to welds. Most cracks were parallel to the weld in the bottom portion of the vessel. Sections were cut out of the vessel containing these cracks and examined using the metallograph, scanning electron microscope, and microprobe to determine the cause of cracking. Most of the cracks originated on the outer surface just outside the weld fusion line in the heat affected zone and propagated along grain boundaries. Crack depth of those sections examined ranged from about 300 to 500 µm. Other cracks were reported to have reached a maximum depth of 0.32-cm (0.125-inch). The primary cause of cracking was the creation of high tensile stresses associated with the CTE differences between the filler metal and the base metal during operation of the vessel in a thermally cyclic environment. This failure mechanism could be described as creep-type fatigue whereby crack propagation might have been aided by the presence of brittle chromium carbides along the grain boundaries, which is indicative of a slightly sensitized microstructure.

Introduction

Hydride reactor vessels are used to produce lithium hydride in an exothermic reaction process. During a recent visual inspection of some of these vessels, circumferential cracks were discovered along the bottom portion of the vessel. One of the cracked vessels is shown in Fig. 1. Construction of the particular vessels in question occurred in the early 90's. A review of the process history revealed that after the factory acceptance test, a crack was found in the welded region of one of the Type 309S stainless steel vessels. The cracked vessel was repaired by machining away the original stainless steel weld metal, re-welding with INCONEL 617® filler wire from the outside, and buttering on the inside with ER-Type 309LT stainless steel wire. Subsequent thermal cycling and radiography of the repaired vessel displayed no cracks so the other vessels were repaired in the same manner.

Figure 1. Hydride reactor vessel

A history summary of the operating life of these vessels and inspection results are provided in Table 1. A typical operating cycle consists of ramping up slowly to about 700°C (1300°F), holding for several hours, and cooling by forced air. Most of the cracks were located along the circumferential welds at the bottom of the vessels. A few sections containing cracks next to the circumferential welds, similar to those shown in Fig. 2, were cut out of two of the vessel walls for failure analysis.

Table 1. History of vessels and results of visual inspections

Vessel Number	Number of Thermal Cycles*	Estimated Hr > 425°C	Inspection Results	Results
1	44	821	4 intermittent cracks < 5 cm long	Rejected
2	33	612	One crack ~ 10 cm long on bottom outside weld	Rejected
3	49	916	One continuous crack on bottom weld	Rejected
4	41	436	One crack on bottom outside weld	Rejected
5	24	433	5 crack-like areas on bottom outside weld	Rejected
6	44	501	6 cracks on bottom outside weld	Rejected
7	45	752	Numerous linear cracks at edge of weld on bottom outside weld	Rejected

* Includes experimental and operational runs

Fig. 2. Cracks adjacent to weld at bottom of vessel.

Examination of Microstructures

Sections of two of the cracked vessels were prepared for metallographic examination to determine the extent of cracking and to examine the integrity of the weld and shell microstructure. Cross sections of the cracked regions were mounted, polished, and etched with a 50% nitric acid-50 %
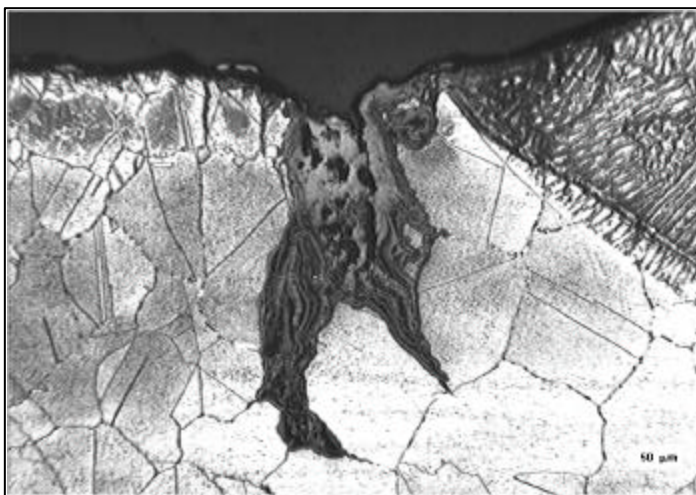

Fig. 3. Cracked region of Vessel No. 6.

water mixture. The microstructure was also examined using the scanning electron microscope (SEM) and backscattered electron imaging. Energy dispersive x-ray (EDX) was used to identify the metallic elements whereas the lighter elements were identified using the electron microprobe. The crack in Vessel #6 is shown in Fig. 3. The crack depth shown in Fig. 3 is approximately 300 μm and the microstructure appears similar to Type 309 stainless steel. The microstructure appears to be slightly sensitized with some evidence of large precipitates in the grain boundaries as shown in Fig. 4. Several specimens from Vessel #7 were prepared in the same manner for metallographic examination.
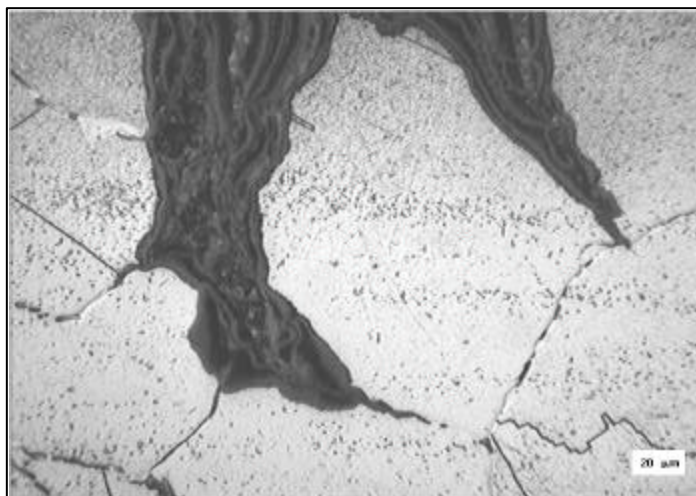

Fig. 4. Intergranular growth and presence of rod-shaped precipitates along grain boundaries.

One of the cracked regions is shown in Fig. 5. The largest of these cracks is approximately 500 μm and some evidence of sensitization is noted by the string of grain boundary precipitates is shown in Fig. 6. A crack approximately 0.3 cm long was discovered in the base plate. Sections were also taken from the weld and base material to verify the filler metal and base metal. Chemical analysis revealed a partially diluted material that indicates that the filler metal is a nickel-based alloy similar to INCONEL 617® and a substrate material that is similar to Type 309 stainless steel as shown in Table 2.

Table 2. Chemical compositions

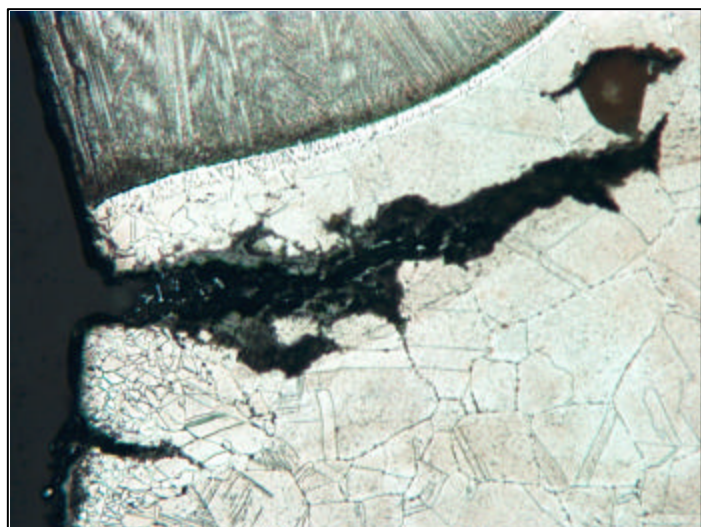| Material	Cr	Si	C	Base
Type 309S	22-24	0.75	0.08	Fe
Ni Alloy	22	0.5	0.07	Ni

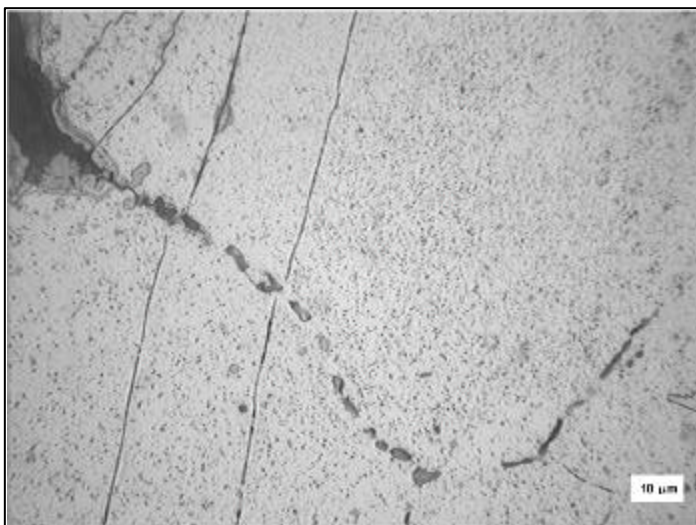**Fig. 5. Cracked region of Vessel No. 7.**

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Fig. 6. Tip of crack from Fig. 5 showing formation of large precipitates along grain boundary.

Grain boundary precipitates, which are seen in the microstructure shown in Fig. 7, near the crack, were determined by EDX to be Cr-rich. Carbon was also detected in the grain boundary precipitates using the electron microprobe.
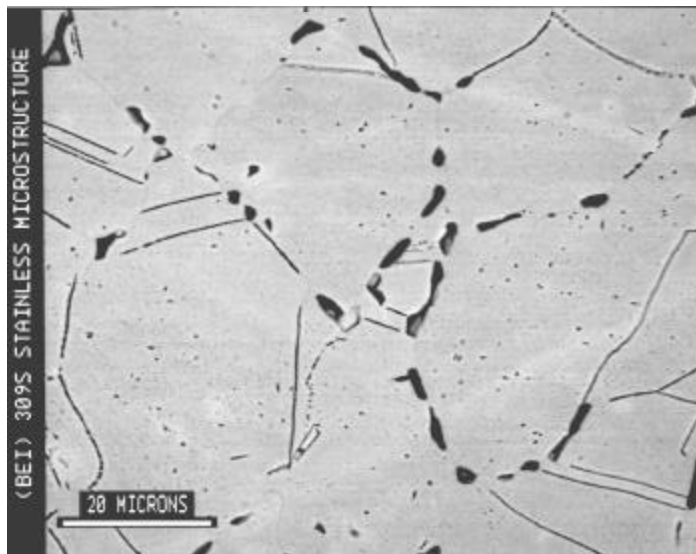

Fig. 7. Section near crack showing precipitates rich in chromium and carbon in Type 309S.

The base material appears to be slightly sensitized with the presence of chromium-rich carbides, and cracking appears to follow some of these grain boundaries where rod-shaped carbides are aligned. Oxide is present along the surface and within the crack opening, especially in the larger, wider cracks. Traditionally, in those cases where sensitization is the primary cause of failure, there are typically Cr-depleted zones along the grain boundaries, cracking is branch-like, and a corrosive element is present. That is not the case here, at least, not in the

classical sense. The effect of having slightly sensitized material and the absence of corrosive attack, other than the presence of general oxide, do not appear substantial enough to be deemed the primary cause of cracking. While these conditions may have contributed to crack nucleation and/or crack propagation, the primary cause of cracking appears to have been caused by highly localized, cyclic stresses in the base material adjacent to the weld. Upon examination of the coefficient of thermal expansion (CTE) properties, the filler metal (INCONEL 617®) is 14.8 μm/m/°C (8.2 x 10^{-6} in/in/°F) whereas the CTE for the base material (Type 309S stainless steel) is 20.7 μm/m/°C (11.5 x 10^{-6} in/in/°F) from room temperature to 700°C (1300°F). That's a difference in CTE of 5.9 x μm/m/°C or 3.3 x 10^{-6} in/in/F between the two metals. Engineering, using linear elastic analysis of the stresses at the weld interface, calculated a maximum stress of 572 MPa (83,000 psi), which exceeds the tensile and yield strength of the stainless steel shell at 700°C.

During the investigation of these cracked vessels, it was reported that vessels of a different design had performed satisfactorily in the past for this same application. Those vessels had curved bottoms and the filler weld metal was believed to be Type 309 stainless steel. According to some of the old records, the material was solution annealed and quenched, which is a standard practice used throughout industry to minimize sensitization in stainless steels. A section of one of the older curved-bottom vessels was analyzed to determine if the filler and base metal was indeed Type 309 stainless steel. However, the carbon results were found to be higher than the 0.08 wt % maximum specified for Type 309 stainless steel. Yet, the vessel apparently showed no evidence of cracking. Since it appears that cracking observed in the current vessels may be associated with some type of creep fatigue mechanism, the role of carbon in the alloy for prolonged periods of time at elevated temperatures becomes an important factor. Reduced carbon in solution in the low-carbon (Type 304L and 316L stainless steel) and stabilized grades (Type 321 and 347 stainless steel) results in reduced creep strength and creep-rupture strength [Ref. 1]. As the hold time at elevated temperature is increased, the effect of rupture ductility becomes more pronounced. The lower the rupture ductility, the lower the creep fatigue endurance for low carbon stainless steels. The higher the carbon content, the higher the creep fatigue strength, but with the higher carbon, the greater the chance of sensitization becomes a problem at these operating conditions. In addition, ASME B&VP code footnotes require the carbon content for Type 309 stainless steel to be 0.04 wt % minimum and 0.08 wt % maximum for use at these temperatures. Consequently, a decision was made not to use the vessel with the higher carbon content. A section of another curved-bottom vessel was examined for cracks, microstructure, and chemical analysis was performed to verify the filler metal. There were no cracks in this section. The microstructure, which is shown in Fig. 8, looked normal, and both the filler metal and base metal were identified as Type 309 stainless steel. In fact, the microstructure showed very little evidence of sensitization, which was rather surprising, because most material handbooks indicate that austenitic stainless steels, such as Type 309 stainless steel, become susceptible to intergranular corrosion when subjected to temperatures in the range of 480°C to 815°C

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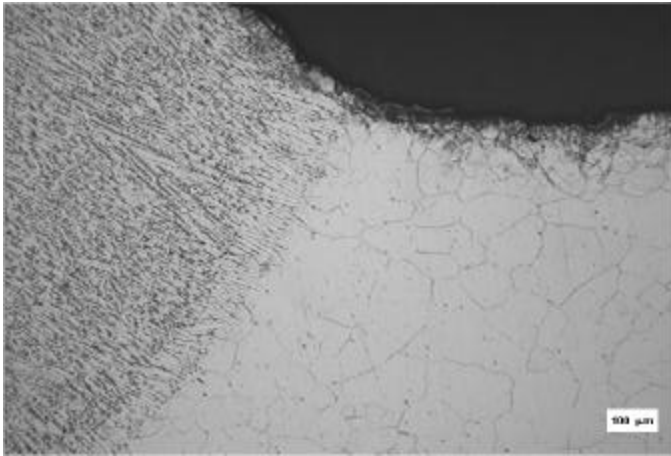(900°F to 1500°F). These conditions occur generally from welding or prolonged service conditions [Ref. 2].

Fig. 8. Welded region of vintage vessel with curved bottom showed very little evidence of sensitization and was crack-free.

Another concern with long-term exposure in the range of 560°C to 990°C (1050°F to 1800°F) is the formation of sigma phases, yet neither condition was prevalent in the older vessels. Even though stabilized stainless steels are often recommended for service in these temperature ranges [Ref. 3], the experience of having operated the older vessels for years with very little evidence of degradation indicates that the design and material selection for the older vessels were satisfactory. With this in mind, a short-term solution was initiated to repair the vessels and keep operations going by combining sections of the curved-bottom vessels with non-cracked sections of the current vessel. One of the few differences in the process equipment between the current process and the "old" process is that forced-air cooling was added to the current process to reduce cycle time and increase production rate. The addition of forced air may have actually increased strain in the welded region and added to the stress magnitude. The bottom of the vessel was changed from a curved bottom to a flat bottom to accommodate a height restriction and process options problem in the new furnace and processing area.

Summary and Conclusions

The primary cause of cracking was determined to be high stresses induced at the weld interface during thermal cycling of the vessel (creep fatigue interaction). The high stresses resulted from the mismatch between the CTE's of the filler metal (nickel-based INCONEL 617®) and the shell (Type 309S stainless steel) and the joint design. Stresses were imposed during prolonged heating at service temperatures (expanding) and forced air cooling (contracting) of the vessel during each cycle of operation. Even though the stainless steel shell exhibited some evidence of sensitization, the effect of sensitization on cracking was determined to play a minor role, perhaps providing a less resistant path for slow crack propagation. The recommendation to change the alloy to a stabilized stainless steel is difficult to justify because of the excellent results observed in the older curved-bottomed Type 309S stainless steel vessels that had matching Type 309S stainless steel filler metal. Based on the results of this investigation, the authors recommend the elimination of the nickel-based filler metal and that new or repaired vessels specify stainless steel filler metal that is compatible with the Type 309S stainless steel shell. Filler metal Type 309H stainless steel, which has a 0.04 wt % minimum carbon specification, may be considered, provided the carbon content meets the specification of 0.08 % maximum. The flat bottom design should be replaced with a curved bottom design to help reduce stresses. Finally, it may be advisable to eliminate forced air cooling or at least evaluate the vessel temperature at which forced air cooling would not contribute to excessive stresses in that region.

Acknowledgements

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